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Imaging Thomson scattering measurements of radiatively heated Xe^{a)}

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Uniform density and temperature Xe plasmas have been produced over >4 mm scale-lengths using x-rays generated in a cylindrical Pb cavity. The cavity is $750\text{ }\mu\text{m}$ in depth and diameter, and is heated by a 300 J, 2 ns square, 1054 nm laser pulse focused to a spot size of $200\text{ }\mu\text{m}$ at the cavity entrance. The plasma is characterized by simultaneous imaging Thomson scattering measurements from both the electron and ion scattering features. The electron feature measurement determines the spatial electron density and temperature profile, and using these parameters as constraints in the ion feature analysis allows an accurate determination of the charge state of the Xe ions. The Thomson scattering probe beam is 40 J, 200 ps, and 527 nm, and is focused to a $100\text{ }\mu\text{m}$ spot size at the entrance of the Pb cavity. Each system has a spatial resolution of $25\text{ }\mu\text{m}$, a temporal resolution of 200 ps (as determined by the probe duration), and a spectral resolution of 2 nm for the electron feature system and 0.025 nm for the ion feature system. The experiment is performed in a Xe filled target chamber at a neutral pressure of 3-10 Torr, and the x-rays produced in the Pb ionize and heat the Xe to a charge state of 20 ± 4 at up to 200 eV electron temperatures.

I. INTRODUCTION

The properties of Xe plasmas are of interest to several areas of physics, including as a buffer gas for inertial confinement fusion power plants. In such a system a large volume (of order 100 m^3) of Xe gas will be heated and ionized by radiation leaving the burning core. Measurements of large scale-length Xe plasmas are necessary for understanding the relevant heating and ionization processes.

Thomson scattering provides a versatile diagnostic technique for determining plasma conditions¹. Scattering from electron plasma waves (the electron feature) allows the accurate determination of local electron density n_e and temperature T_e ², while scattering from ion-acoustic waves (the ion feature) is sensitive to charge state Z , electron temperature, ion temperature T_i , and plasma flow velocity³. By imaging the scattering signal and dispersing the scattered light a spatial plasma profile can be determined.

II. EXPERIMENT

A recent experiment has produced and diagnosed a large scale-length radiatively heated Xe plasma. The experiment was performed with the Janus laser system at the Jupiter Laser Facility, Lawrence Livermore National Laboratory. A radiation cavity is produced by creating a cylindrical dimple in a solid Pb brick; the cavity is $750\text{ }\mu\text{m}$ in diameter and depth. It is heated by a 300 J, 2 ns square, 1054 nm laser pulse focused to a spot size of

$200\text{ }\mu\text{m}$ at the entrance of the cavity. As shown in Fig. 1, the Pb is aligned such that the heating laser axis is 27 degrees from the target normal axis. The surrounding region contains a uniform Xe background at a pressure of 3-10 Torr, achieved by filling the entire 3 m^3 target chamber with Xe.

X-rays produced in the cavity heat and ionize the Xe in front of the target, and the resulting plasma is diagnosed with Thomson scattering. The Thomson probe beam is aligned along the axis of the cylindrical cavity, and delivers 40 J of 527 nm laser light in a 200 ps pulse to a $100\text{ }\mu\text{m}$ spot size at the entrance of the Pb cavity. The probe beam is timed to arrive at the cavity entrance 10 ns after the arrival of the rising edge of the heating pulse. The scattered light is collected 90 degrees from both the propagation axis and polarization axis of the probe beam (parallel to the surface of the Pb).

The scattered light is collimated by an $f/4$ collection optic and transported to a beamsplitter which reflects 522-542 nm light and is otherwise transmissive. The transmitted light is focused at $f/20$ to the entrance slit of a $1/3\text{ m}$ spectrometer that is coupled to a 16-bit charge-coupled device (CCD) camera. The spectrometer disperses light with a 150 g/mm diffraction grating, providing a spectral (spatial) field of view of 260 nm (2.7 mm); this system resolves the electron feature of Thomson scattering.

The light reflected by the beamsplitter is sent to a similar system which provides higher dispersion and resolves the ion feature of Thomson scattering. The increased dispersion is achieved with a 1 m spectrometer (using a 3600 g/mm grating) which is coupled to a second 16-bit CCD camera. The spectral (spatial) field of view of this system is 3.2 nm (3.5 mm).

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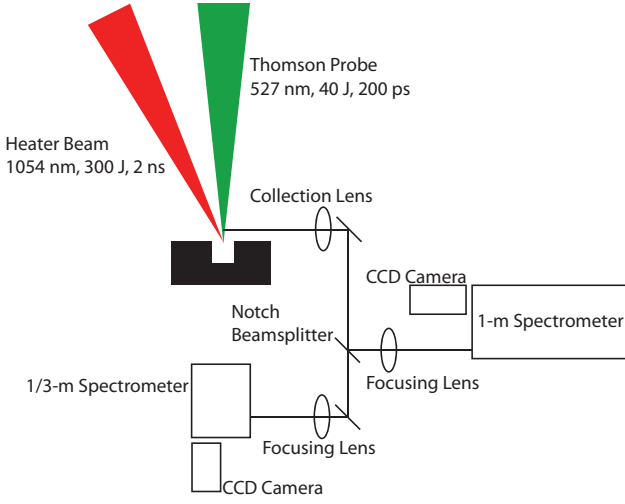


FIG. 1. The experimental setup with the Janus laser system. The Thomson scattering probe beam is polarized out of the page.

III. RESULTS

Fig. 2 shows a background-subtracted Thomson scattering image from the electron feature diagnostic, as well as a spectral lineout from the data. The Thomson scattering form factor is given by

$$S(k, \omega) = \frac{2\pi}{k} \left[\left| 1 - \frac{\chi_e}{\epsilon} \right|^2 F_e \left(\frac{\omega}{k} \right) + Z \left| \frac{\chi_e}{\epsilon} \right|^2 F_i \left(\frac{\omega}{k} \right) \right] \quad (1)$$

where χ_e and χ_i are the electron and ion susceptibilities, F_e and F_i are the electron and ion distribution functions (here assumed to be Maxwellians), $\epsilon = 1 + \chi_e + \chi_i$, and k and ω are the wavenumber and frequency of the wave responsible for the scattering. For an incident Thomson scattering probe beam wavenumber k_0 and frequency ω_0 the momentum and energy conservation relations are given by

$$\mathbf{k}_s = \mathbf{k}_0 + \mathbf{k} \quad (2)$$

$$\omega_s = \omega_0 + \omega \quad (3)$$

where k_s (ω_s) is the wavenumber (frequency) of the Thomson-scattered light. By fitting the Thomson scattering form factor to the experimental data the electron density and temperature are determined.

The spectral separation of the peaks in the scattered spectrum is determined by the electron plasma wave frequency, which from the Bohm-Gross dispersion relation depends almost entirely on the electron density at these temperatures. For a fixed density the structure of an individual peak is sensitive to the wave Landau damping, which is proportional to the electron temperature.

Electron Thomson Fit

$n_e = 5.6 \pm 0.5 \times 10^{18} / \text{cc}$
 $T_e = 170 \pm 15 \text{ eV}$
 $\alpha = 2.04$
 Red points included in fit

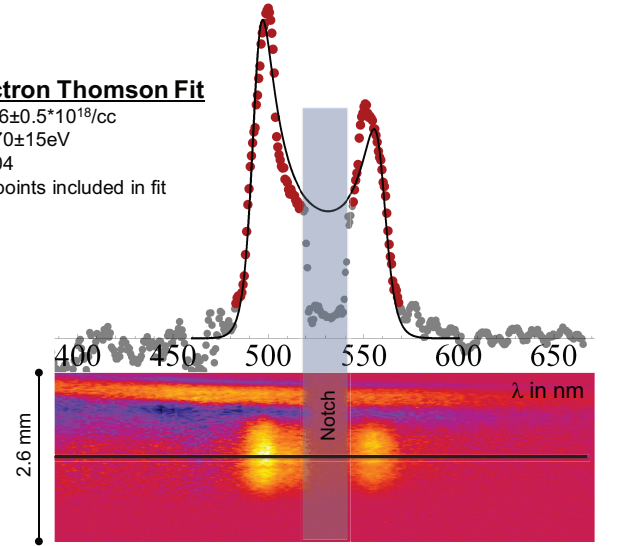


FIG. 2. Background-subtracted false-color electron feature Thomson scattering data in a 10 Torr Xe backfill. The lineout is taken at the position indicated in the figure.

ITS Xe

$Z = 20 \pm 4$

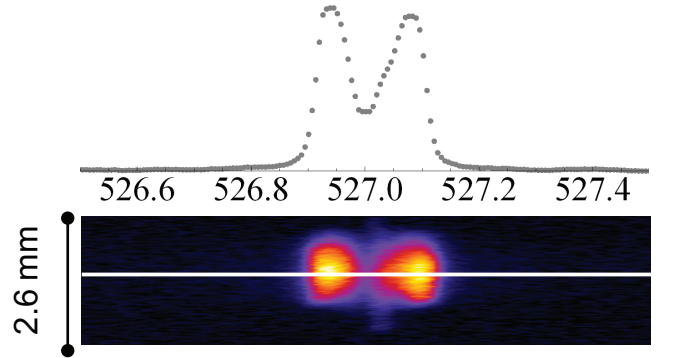


FIG. 3. false-color ION feature Thomson scattering data in a 10 Torr Xe backfill. The lineout is taken at the position indicated in the figure. Using the electron temperature determined from the electron feature fit the charge state can be determined from the ion feature.

By varying both parameters the calculated spectrum is found to best recreate the measured data for a unique density and temperature, with error bars determined by the range of parameters that still force the fit through the noise on the data. For the data shown in Fig. 2 the best fit corresponds to an electron density of $5.6 \times 10^{18} \text{ cm}^{-3}$ and an electron temperature of 170 eV; the uncertainty in both parameters is 10%.

Fig. 3 shows the simultaneous measurement of the ion feature scattering. Here the separation of the peaks in the spectrum is determined by the ion-acoustic wave fre-

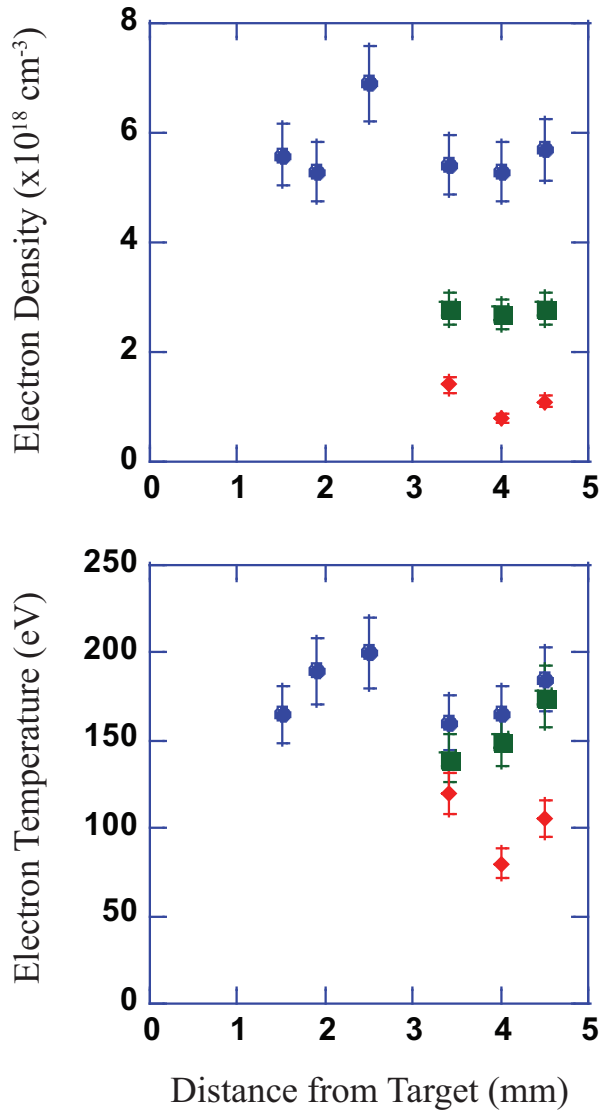


FIG. 4. The Xe plasma spatial density and temperature profiles. The blue circles correspond to a Xe backing pressure of 10 Torr, the green squares to 5.5 Torr, and the red diamonds to 3 Torr. The plasma properties are uniform over >4 mm.

quency, which is proportional to $\sqrt{ZT_e}$. By constraining the electron temperature to the electron feature value, the ion charge state can be measured; here it is found to be $Z=20\pm4$. The Xe backfill pressure was 10 Torr, which corresponds to a neutral Xe density 3.4×10^{17} cm $^{-3}$. From the electron density measured with Thomson scattering the charge state is 16.5, which is within the error bar of the charge state measurement.

The Thomson scattering spectrum is analyzed at various locations along the direction normal to the target surface. The electron density and temperature from each measurement are shown in Fig. 4. In order to determine the plasma conditions further than 2.5 mm from the target the target is moved 2 mm backward along the target normal axis to put a different region of plasma within the field of view of the Thomson scattering system; the laser beam pointing and focusing are subsequently shifted to compensate.

The measurements indicate that the Xe plasma profile is uniform in both density and temperature over >4 mm from the target surface. Additionally, by reducing the Xe pressure the electron density is reduced by the corresponding amount. These measurements demonstrate a technique for producing long scale-length uniform Xe plasmas, which are relevant to several physics applications. Future experiments will seek to measure the late time cooling of the Xe using spectroscopy and optical pyrometry.

IV. ACKNOWLEDGEMENTS

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